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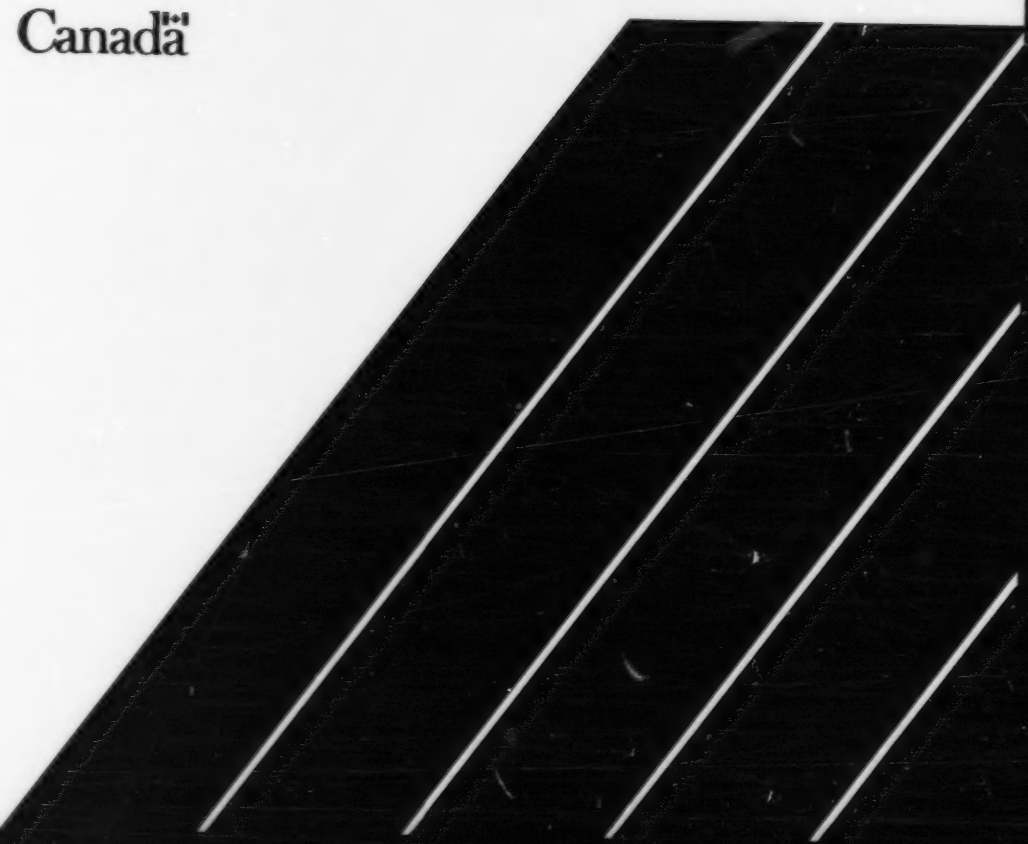
SCALE EFFECTS TESTING ON ROCK SAMPLES FROM
LAC DU BONNET, MANITOBA: REPORT #2

RAND JACKSON

MRL 90-075(TR)

August, 1990

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by

Rand Jackson*

ABSTRACT

Compressive and shear wave velocity measurements, as well as uniaxial compression testing, were conducted on laboratory samples of grey granite obtained from the site of Atomic Energy of Canada Limited's Underground Research Laboratory (URL). Seven specimen diameters ranging from 33 mm to 294 mm were studied in an attempt to determine what, if any, the effects of scale were on the predominant rock type in the vicinity of the URL. Specimens up to 63 mm, while showing some variation, indicated no trends with increasing specimen size. This is attributed to the predominant influence of surface defects in governing the uniaxial mechanical properties in samples of this size. Definite trends of decreasing uniaxial compressive strength and tangent modulus of elasticity, however, were noted as specimen diameter increased from 63 mm to 294 mm. Poisson's ratios determined at 50% of failure load showed little dependence on specimen size.

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Keywords

Rock Properties, Mechanical, Young's Tangent Modulus, Poisson's Ratio, Uniaxial Compressive Strength, Velocity, Lac du Bonnet, Scale Effects

VÉRIFICATION DE L'EFFET D'ÉCHELLE DANS DES CAROTTES
D'ÉCHANTILLONS PROVENANT DU LAC DU BONNET, MANITOBA:
RAPPORT n° 2

par

Rand Jackson*

On a mesuré la vitesse de l'onde de compression et de l'onde transversale ainsi que la compression uniaxiale dans des échantillons pour laboratoire d'un granite gris provenant de l'emplacement du Laboratoire de recherche souterrain (LRS) d'Énergie atomique du Canada Limitée. Sept échantillons d'un diamètre allant de 33 mm à 294 mm ont été examinés afin de déterminer quels étaient les effets d'échelle, le cas échéant, sur le lithotype principal à proximité du LRS. Bien que les échantillons dont le diamètre atteint jusqu'à 63 mm présentent certaines variations, ils ne montrent aucune tendance à mesure qu'augmente la dimension de l'échantillon. On attribue ce phénomène à l'influence prédominante des défauts de surface qui contrôlent les propriétés mécaniques uniaxiales dans les échantillons de cette grosseur. Or, il y a une réduction manifeste de la résistance à la compression uniaxiale et du module tangent d'élasticité au fur et à mesure que le diamètre de l'échantillon augmente pour passer de 63 à 294 mm. Le coefficient de Poisson déterminé à une charge de rupture de 50% varie peu en fonction de la dimension de l'échantillon.

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Mots clés

coefficient de Poisson, effets d'échelle, lac du Bonnet, mécanique, module tangent de Young, propriété des roches, résistance à la compression uniaxiale, vitesse

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INTRODUCTION

As part of the Canadian Nuclear Fuel Waste Management Program, Atomic Energy of Canada Limited (AECL) is characterizing various rock formations within the Canadian Shield to determine their suitability for the long-term disposal of high-level nuclear wastes. The program includes the construction of the Underground Research Laboratory (URL) in the Lac du Bonnet Batholith near Pinawa, Manitoba to provide an opportunity for extensive insitu investigations. In preparation for these investigations, considerable laboratory testing has been conducted to supply numerical modellers with input data for use in predicting possible ground movement and changes in the stress field resulting from excavation and anticipated thermal loading. The mechanical properties data are also required by engineers for the design of long-term experiments to be carried out at the URL. At present, the vast majority of laboratory testing has utilized 45-mm diameter specimens, while insitu experiments will obviously involve much greater volumes of rock.

The effects of specimen size on the mechanical properties of rocks have been studied by several authors with varying results. Hodgson and Cook (1970) found no scale effect on quartzite and shale specimens up to 15 cm in diameter when special precautions were taken to ensure uniform loading. Hoskins and Horino (1969), however, observed net increases in strength for Kansas limestone, Carthage marble and Longmont sandstone up to specimen diameters of 5 to 8 cm after which increasing the specimen diameter resulted in a decrease in strength. Salda granite studied by the same investigators exhibited a continuous decrease in strength with increasing specimen diameter. Lundborg (1966) also noted decreases in strength with increasing sample size for granitic specimens, although to a different degree. A literature search on the influence of size on deformation characteristics revealed that very little has been published. In general, other investigators reported that there is some reduction in the elastic modulus with increasing specimen size (Lama, 1970; Hudson et al., 1971).

This lack of consensus indicated that it would be desirable to determine the site-specific scale effects on the various properties of the Lac du Bonnet granite. A preliminary investigation was conducted by the Canada Centre for Mineral and Energy Technology (CANMET) in co-operation with AECL to study the effect of specimen size on the ambient-temperature uniaxial mechanical properties of the grey granite found at the 240-m level of the URL. While results from this study indicated some dependence between mechanical response and specimen size, it was difficult to define precise relationships given the amount of data available (Jackson, 1989). Results from a second test series utilizing 100, 194 and 294-mm diameter specimens made it possible to discern definite trends and compare these with other established empirical relationships.

This report summarizes the individual test results obtained for the three additional specimen diameters, indicates trends in mechanical response with specimen size and provides a comparison between observed behaviour and predictions made using the Hoek and Brown (1980), Gyenge and Herget (1977) and Weibull (1939) models.

SAMPLING AND SPECIMEN PREPARATION

Samples used in these tests were obtained from boreholes 001-249-MOD2, 208-016-S1, 209-033-AS1 and 209-055-OC3 located at the 240 m level of the URL (Figure 1). The rock is a massive, grey, medium- to coarse-grained granite, composed of quartz, K-feldspar, plagioclase and biotite. Thirteen specimens (five 100 mm, four 194 mm and four 294 mm diameters) were prepared for uniaxial compression testing in accordance with methods suggested by the International Society for Rock Mechanics (Brown, 1981) and procedures described in CANMET's Pit Slope Manual Supplement 3-5 (Gyenge and Ladanyi, 1977). Table 1 provides a summary of the borehole number, depth from collar, dimensions and density for specimens used in the second test series.

Table 1: Summary of Specimen Dimensions

Specimen identification	Sample depth (m)	Length (mm)	Diameter (mm)	Mass (g)	Density (Mg/m ³)
209-055-OC3	1.99	226.67	101.72	4838.2	2.63
	2.27	228.41	102.01	4909.5	2.63
	2.55	227.08	101.53	4875.5	2.65
	3.88	227.80	101.63	4850.4	2.62
	4.17	225.60	101.76	4837.1	2.64
001-249-MOD2	0.00	474	194.58	N/A	N/A
	0.56	459	194.48	N/A	N/A
209-033-AS1	1.86	476	192.82	N/A	N/A
	2.40	482	194.24	N/A	N/A
208-016-S1	0.24	661	294.13	N/A	N/A
	0.96	654	293.05	N/A	N/A
	1.80	661	294.51	N/A	N/A
	2.50	657	294.20	N/A	N/A

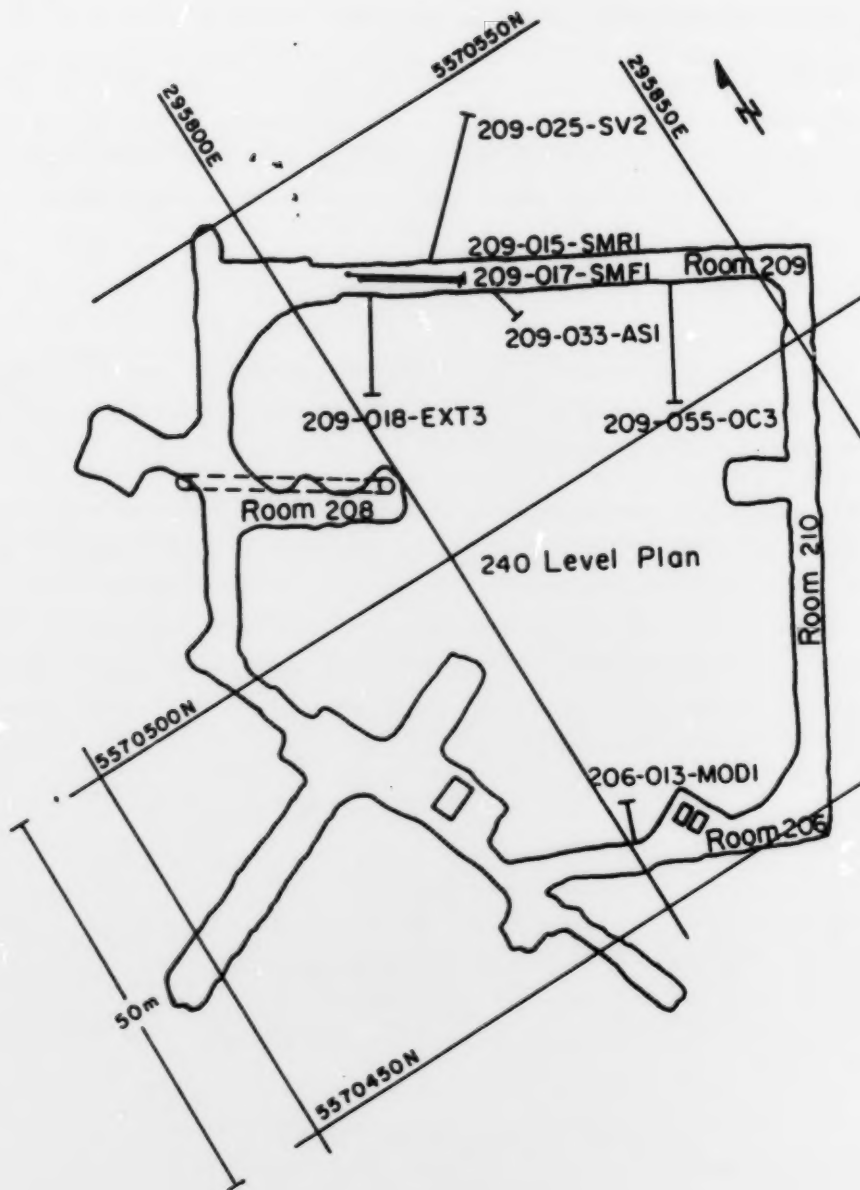


Figure 1: Location of scale effects boreholes on the 240 m level of the URL

The reader is referred to CANMET Report MRL 89-39(TR) for individual specimen details of the other sample sizes used for analysis.

Axial deformation measurements were made using two diametrically opposed strain gauges mounted at mid-height on each of the specimens. Two circumferential strain gauges were similarly mounted at 90° to the axial gauges to measure lateral strain. In both cases, the two strain gauges were connected in series to form a single active gauge.

WAVE VELOCITY MEASUREMENTS

Due to limitations in the equipment, it was not possible to perform ultrasonic pulse measurements on the 194 and 294 mm diameter specimens. However, compression and shear wave velocities were determined for the 100 mm diameter specimens.

The testing equipment consisted of: transmitting and receiving platens containing piezoelectric transducers, a high-voltage pulse generator, a signal amplifier and a Tektronix Type 555 dual-beam oscilloscope equipped with delay sweep and a time base resolution of 0.01 μ s. The compressional and shear wave velocities were determined by dividing the specimen length by the wave travel time through the specimen. Dynamic properties including Young's modulus, shear modulus and Poisson's ratio were then calculated using the following equations:

Dynamic Young's Modulus:

$$E_d = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \quad (1)$$

where E_d = dynamic Young's modulus
 V_s = shear wave velocity
 V_p = compressional wave velocity
 ρ = density

Dynamic Shear Modulus:

$$G_d = \rho V_s^2 \quad (2)$$

where G_d = dynamic shear modulus

Dynamic Poisson's Ratio:

$$\nu_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (3)$$

where ν_d = dynamic Poisson's ratio.

Table 2 summarizes the velocity measurements and corresponding dynamic properties for the 100 mm diameter specimens. The mean dynamic properties of all the specimen sizes subjected to velocity testing are contained in Table 3.

Table 2 - Summary of Ultrasonic Velocity Properties: 100 mm Diameter Specimens

Drill Hole	Sample Depth (m)	P-wave Velocity (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
209-055-OC3	1.990	4.21	2.33	14.32	36.61	0.28
	2.268	4.10	2.31	14.07	35.63	0.27
	2.548	4.16	2.44	15.75	39.03	0.24
	3.880	4.23	2.39	14.95	37.86	0.27
	4.173	4.32	2.51	16.68	41.49	0.24

Table 3: Mean Dynamic Properties

Specimen Diameter (mm)	P-wave Velocity (km/s)	S-wave Velocity (km/s)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
33	4.78 (0.10)	2.30 (0.07)	14.03 (0.81)	37.80 (1.77)	0.35 (0.02)
45	4.76 (0.10)	2.66 (0.10)	18.62 (1.32)	47.33 (2.82)	0.27 (0.03)
63	3.58 (0.11)	2.16 (0.06)	12.35 (1.32)	29.86 (1.32)	0.21 (0.03)
100	4.20 (0.08)	2.40 (0.08)	16.68 (1.07)	38.12 (2.28)	0.24 (0.02)
141	4.25 (0.11)	2.74 (0.11)	20.19 (1.12)	45.63 (2.22)	0.13 (0.02)

UNIAXIAL COMPRESSION TESTS

Uniaxial compression tests were conducted to determine the following properties:

- 1) uniaxial compressive strength
- 2) tangent Young's modulus of elasticity, E_t
- 3) Poisson's ratio, ν

One hundred millimeter samples were tested on an MTS 880 Rock Mechanics Test System with stress/strain measurements being recorded every three seconds. Linear variable differential transducers (LVDTs) were also used with the MTS system to provide

redundant measurements of axial deformation. Specimens with diameters of 194 and 294 mm were tested on a Gilmore Model 302 D, 18,000-kN testing machine. All samples were compressed using loading rates in the range of 0.5 to 1.0 MPa/s.

Stress/strain curves were computer generated using analog outputs from the strain bridges and press load cell and are illustrated in Figures 9 through 22. Tangent Young's moduli of elasticity, E_t , were calculated for each specimen at stress levels of 10, 20, 30, 40, 50 and 60 MPa and at 50% and 75% of the failure load. The ratio of the tangent to the axial strain curve to the tangent of the circumferential strain curve at 50% failure load was used to determine Poisson's ratio values. Tables 4, 5 and 6 summarize the mean uniaxial mechanical properties for the individual specimens used for the 100, 194 and 294 mm sample suites, respectively while Table 7 contains the mean results and standard deviations (in brackets) for all specimen sizes used in the analyses.

OBSERVATIONS AND DISCUSSION

DYNAMIC ELASTIC PROPERTIES

The propagation of longitudinal or compressive waves in rock depends on several factors including rock type, texture, density, porosity, stress, anisotropy, water content and temperature (Lama and Vutukuri, 1978). As Figure 2 indicates, the Lac du Bonnet granite shows considerable variation in wave velocities despite being a comparatively homogeneous material *insitu*. Higher velocities observed for the 33 and 45 mm diameter samples probably relate to coupling effects due to the relative sizes of the specimens and the velocity heads (51 mm in diameter) used for the measurements. However, as the specimen diameter exceeds that of the velocity heads, a considerable drop in both the compressive and shear wave velocities was observed. Further increases in diameter resulted in a gradual increase the wave velocities and is likely a result of less sample disturbance in the larger specimens.

As might be expected, values determined for the dynamic Young's and shear moduli follow the same trends noted for the velocity measurements (Figure 3). It is interesting to note, however, that, with the exception of the 100 mm diameter results, the dynamic Poisson's ratio decreases continually with increasing sample size (Figure 4).

Table 3: Summary of Uniaxial Compression Properties: 100 mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)					Poisson's Ratio	
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	50%	75%
209-055-OC3 1.990	195	26.18	31.12	39.85	47.22	52.13	55.42	59.07
2.268	192	27.26	35.22	44.01	51.18	56.24	59.84	65.12
2.548	175	25.28	33.79	42.61	49.65	54.27	57.45	60.99
3.880	191	31.42	37.27	45.50	52.31	56.72	59.39	61.13
4.173	196	27.83	34.58	43.92	51.47	56.48	59.74	63.52
							65.97	69.70
								0.29
								0.18
								0.15
								0.23
								0.20

Table 4: Summary of Uniaxial Compression Properties: 194 mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)					Poisson's Ratio	
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	50%	75%
001-249-MOD2 0.00	152	19.58	26.40	33.66	39.84	45.35	49.95	55.42
001-249-MOD2 0.56	163	26.38	31.10	36.78	42.44	47.99	52.88	60.07
209-033-AS1 1.86	148	32.64	37.79	44.24	49.46	53.86	57.44	60.84
209-033-AS1 2.40	160	33.96	39.57	45.63	50.66	54.98	58.60	63.56
							67.04	71.71
								0.18
								0.16
								0.18
								0.22

Table 5: Summary of Uniaxial Compression Properties: 294 mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)					Poisson's Ratio	
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	50%	75%
209-055-S1 0.245	162	26.28	37.34	46.97	53.42	57.34	59.37	59.07
0.960	162	28.17	39.42	49.25	55.51	59.73	62.28	65.12
1.800	154	17.46	27.34	35.96	42.08	46.39	49.47	60.99
2.500	186	22.37	33.10	42.49	48.55	52.61	55.23	61.13
							64.79	69.70
								0.29
								0.30
								0.25
								0.28

Table 7: Mean Uniaxial Mechanical Properties

	Stress Level (MPa)	Specimen Diameter						
		33 mm	45 mm	63 mm	100 mm	141 mm	194 mm	294 mm
Uniaxial Compressive Strength (MPa)	0.10	195 (7)	171 (9)	199 (11)	190 (9)	171 (3)	156 (7)	166 (14)
Tangent Modulus of Elasticity (GPa)	10	38.09 (5.31)	39.74 (3.49)	32.08 (2.21)	27.59 (2.35)	28.18 (2.76)	28.14 (6.60)	23.57 (4.74)
	20	49.25 (4.64)	50.73 (2.51)	43.50 (1.82)	34.40 (2.24)	37.56 (1.97)	33.72 (6.09)	34.30 (5.33)
	30	57.38 (4.23)	57.95 (2.39)	51.30 (1.58)	43.18 (2.12)	46.37 (1.71)	40.08 (5.78)	43.67 (5.86)
	40	62.60 (4.05)	62.76 (2.32)	56.74 (1.60)	50.37 (2.00)	52.27 (1.67)	45.60 (5.28)	50.14 (6.29)
	50	66.61 (3.90)	65.80 (2.22)	60.59 (1.66)	55.17 (1.96)	56.34 (1.68)	50.54 (4.62)	54.02 (5.88)
	60	68.87 (3.74)	67.37 (2.07)	63.21 (1.72)	58.37 (1.91)	59.09 (1.69)	54.72 (4.02)	56.59 (5.56)
	50%	69.07 (2.91)	68.19 (2.17)	65.66 (2.04)	61.97 (2.37)	61.65 (1.80)	59.97 (3.38)	60.23 (3.47)
	75%	67.06 (3.98)	65.09 (3.42)	62.19 (0.06)	62.21 (3.76)	62.07 (3.42)	65.45 (3.05)	57.07 (3.88)
Poisson's Ratio	50%	0.42 (0.06)	0.31 (0.05)	0.32 (0.06)	0.21 (0.05)	0.33 (0.06)	0.20 (0.04)	0.28 (0.02)

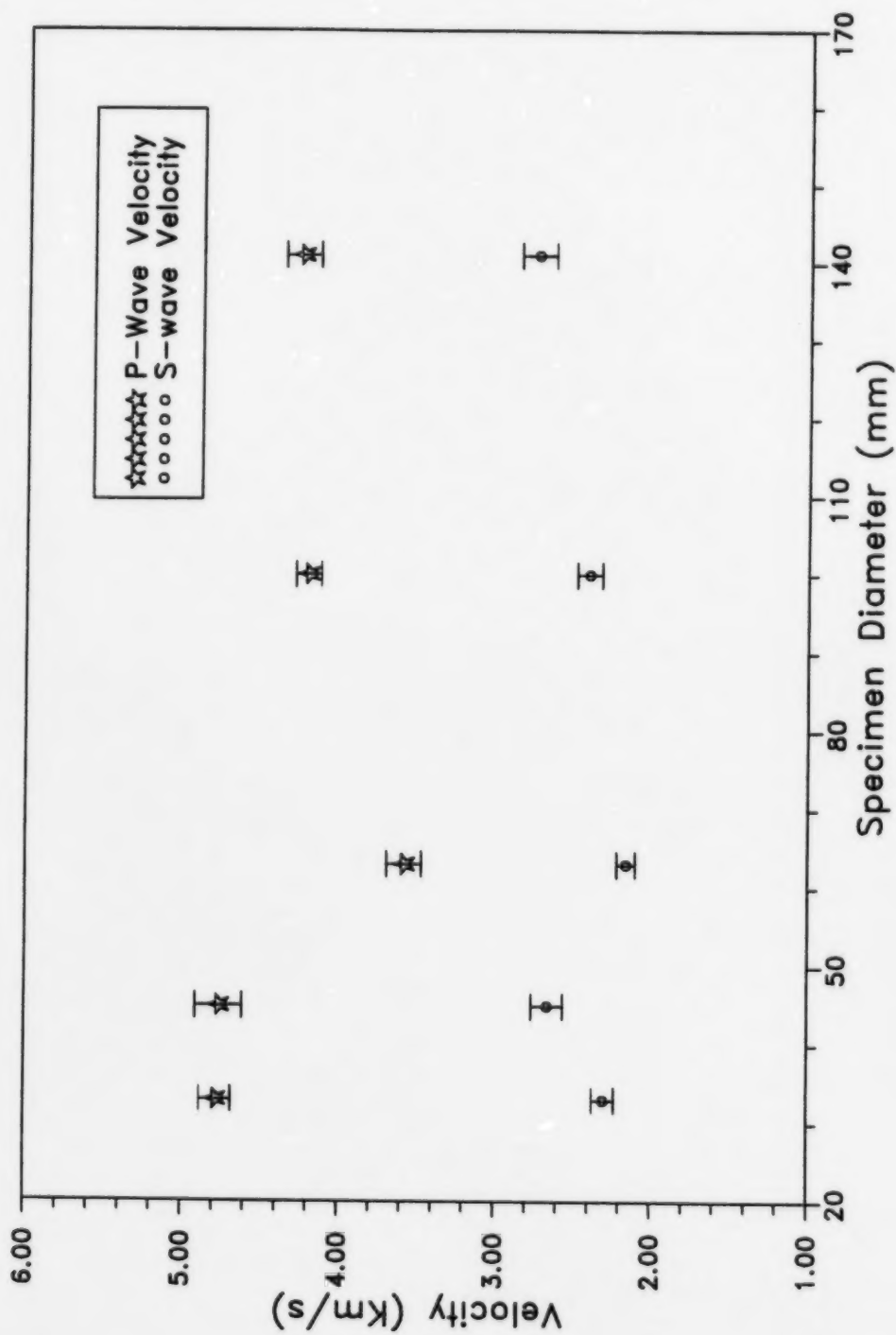


Figure 2: P- and S-wave velocities versus specimen diameter

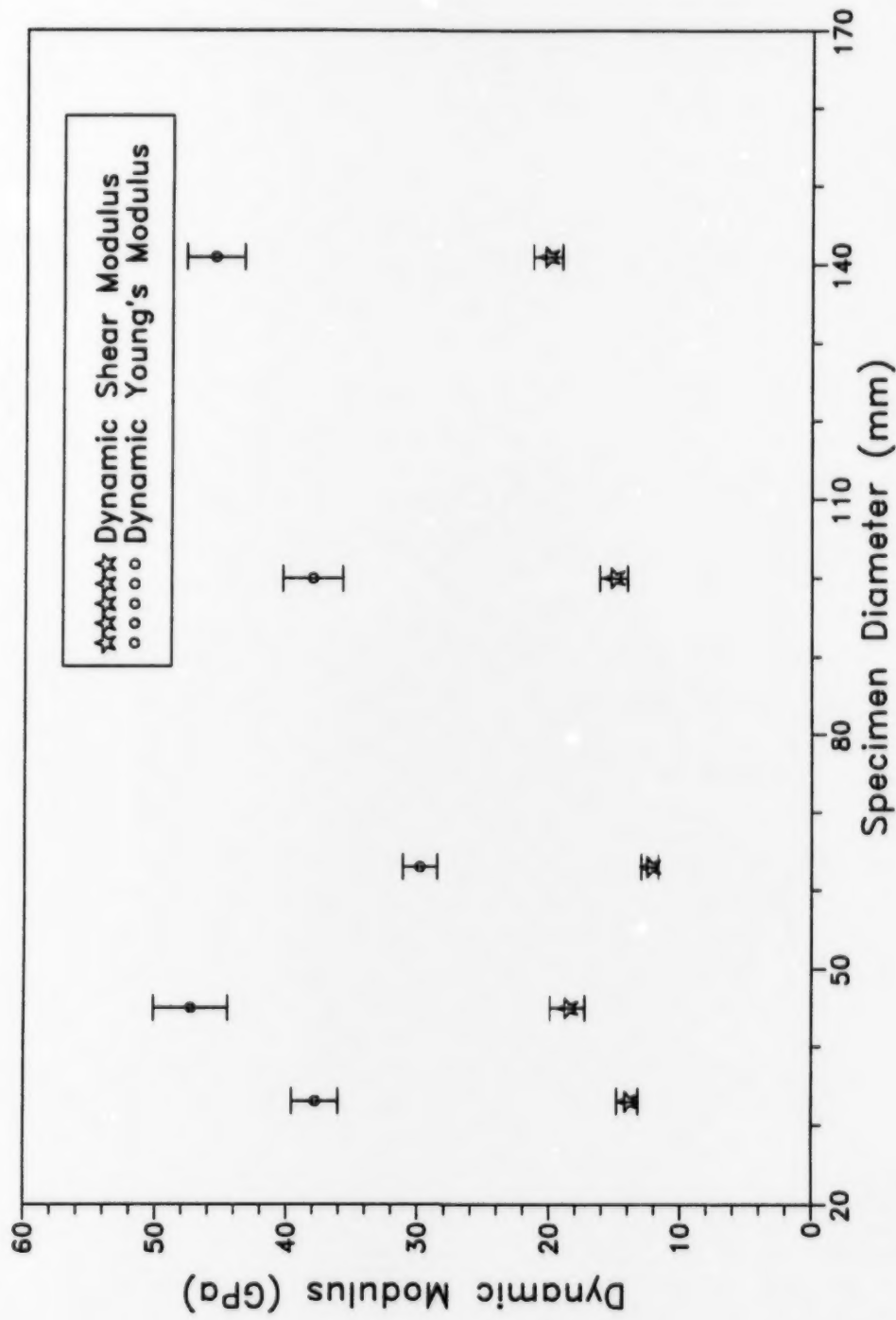


Figure 3: Dynamic shear and Young's moduli versus specimen diameter

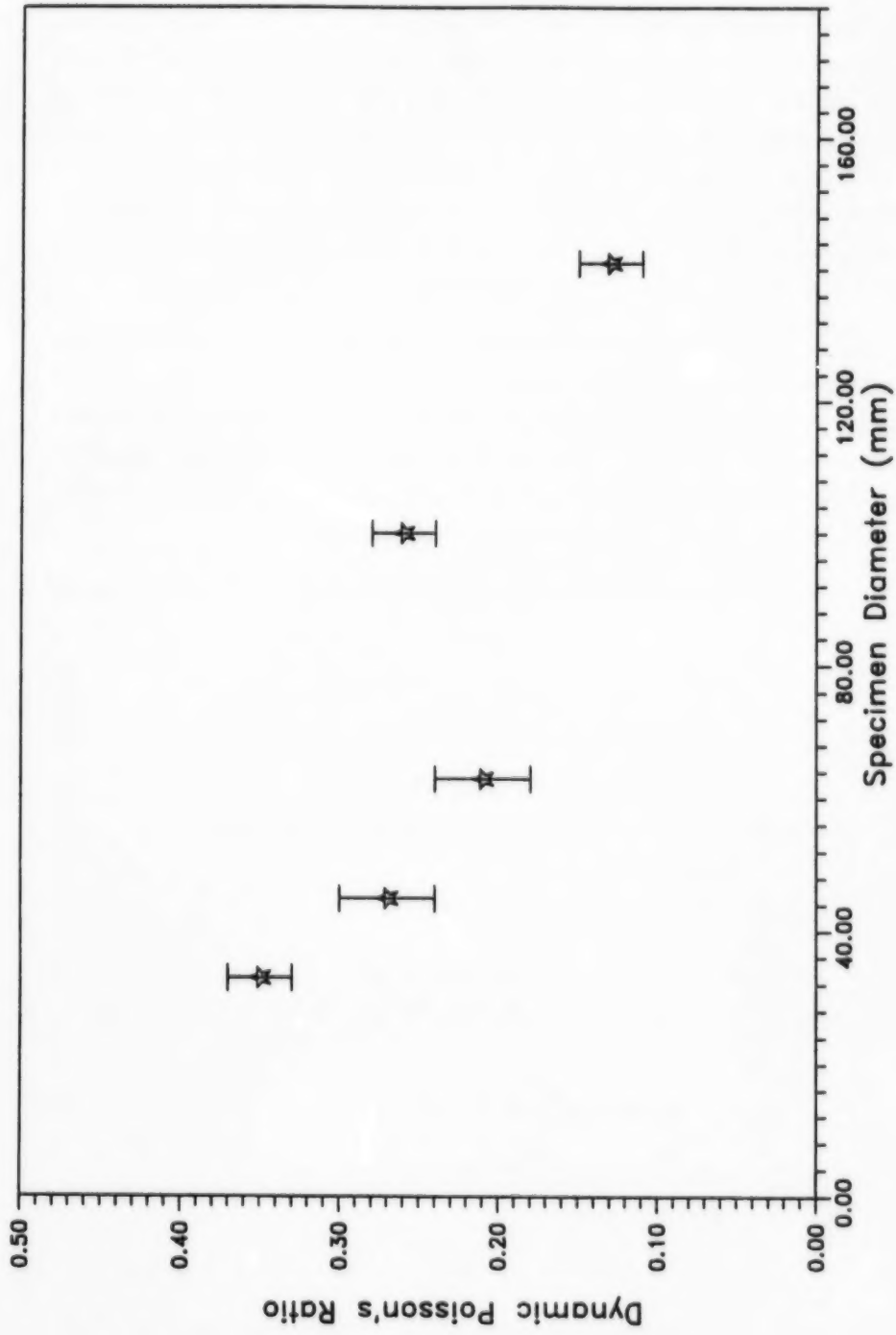


Figure 4: Dynamic Poisson's Ratio versus specimen diameter

UNIAXIAL COMPRESSIVE STRENGTH

Historically, the effect of sample size on the mechanical properties of rock has been attributed to two competing mechanisms (Vutukuri et al., 1974). On one hand, an increase in specimen volume results in the increased probability that critical flaws exist in the sample causing an apparent lowering of strength. On the other hand, as the specimen diameter decreases, larger surface area to volume ratios cause surface imperfections to have greater impact resulting in undue stress concentrations and a lowering of the compressive strength. While the former mechanism depends on inherent properties of the rock mass, the latter is more a result of specimen sampling, handling and the interaction between it and the testing apparatus.

The results of the scale effects studies described here and those of Hoskins and Horino (1969) and Dhir and Sangha (1973) seem to indicate that surface flaws are the predominant influence in determining the uniaxial compressive strength for samples less than 63 mm in diameter. It is apparent, however, that increases in specimen diameter from 63 to 194 mm have resulted in a significant 22% decrease in the observed uniaxial compressive strength for the Lac du Bonnet grey granite (Figure 5).

Hoek and Brown (1980) suggested that the scale effects curve could be adequately described according to;

$$\sigma_c = \sigma_{c50} \left(\frac{50}{d} \right)^{0.18} \quad (4)$$

where σ_c = predicted uniaxial strength
 σ_{c50} = uniaxial compressive strength for a 50 mm
 diameter specimen
 d = specimen diameter in mm.

Because 50 mm diameter specimens have not been tested as part of this program, the results of the 63 mm test series have been substituted into Equation 4 yielding;

$$\sigma_c = \sigma_{c63} \left(\frac{63}{d} \right)^{0.18} \quad (5)$$

where σ_{c63} = uniaxial compressive strength for a 63 mm
 diameter specimen

This, in turn, has been used to generate the Hoek and Brown curve in Figure 6.

Gyenge and Herget (1977) used a similar empirical formula, but suggested that, where possible, the exponent in Equation 5 should be determined according to the best

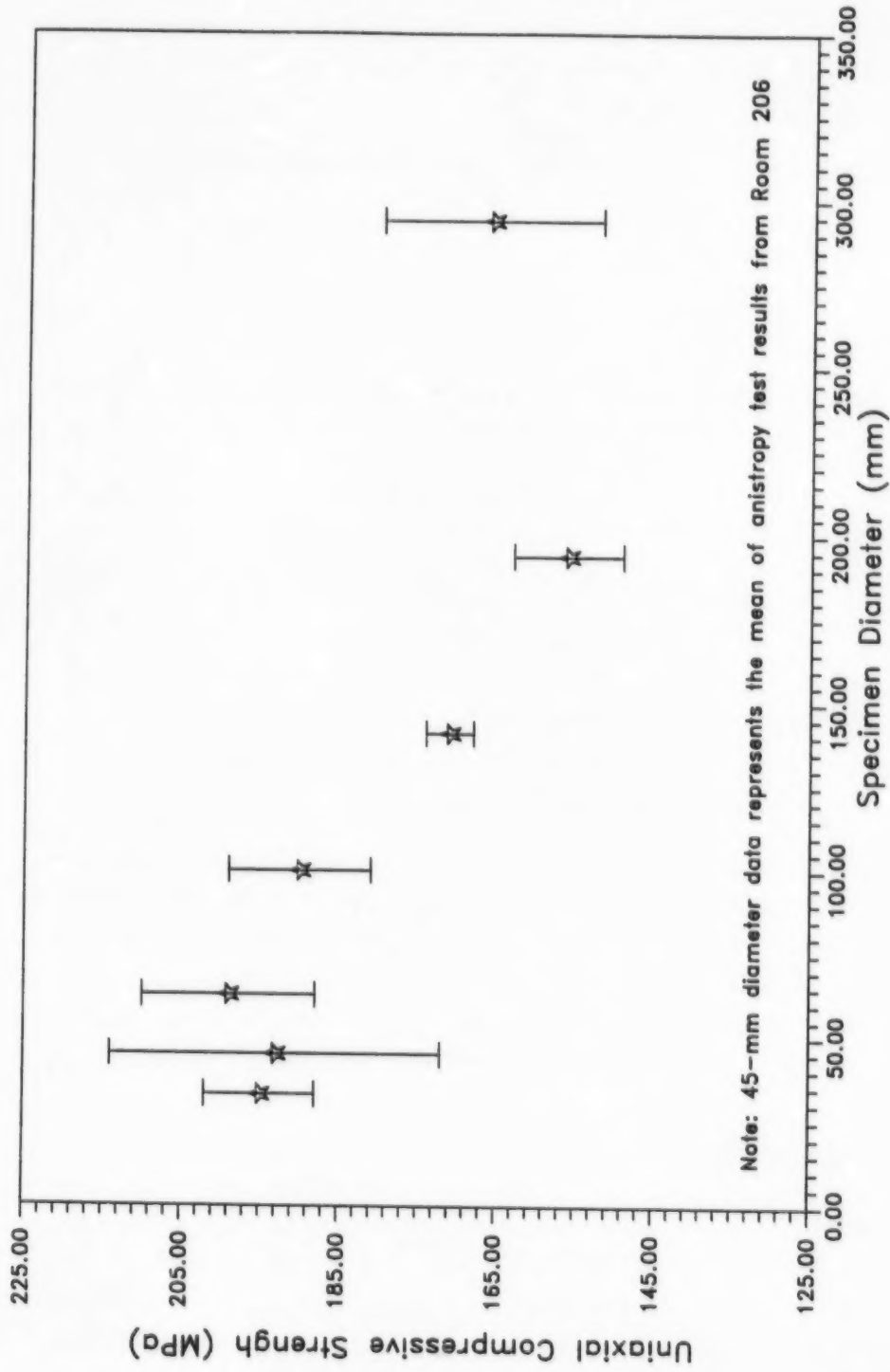


Figure 5: Uniaxial compressive strength versus specimen diameter

fit of data obtained from an appropriate scale-effects test program. Accordingly, a fit was performed using the data derived from this study. However, the results of the 33 mm and 45 mm diameter tests were excluded from the fitting process since their behaviour appeared to be governed predominantly by surface, as opposed to internal, defects.

This analysis resulted in the Gygge and Herget curve shown in Figure 6 and is defined by;

$$\sigma_c = \sigma_{c63} \left(\frac{63}{d} \right)^{0.16} \quad (6)$$

where σ_{c63} = uniaxial compressive strength for a 63 mm diameter specimen.

The Weibull or "weakest link" theory (1939) states that the effect of specimen size can be predicted according to the equation;

$$m \log \left(\frac{\sigma_{c1}}{\sigma_{c2}} \right) = \log \left(\frac{V_2}{V_1} \right) \quad (7)$$

where σ_{c1} = uniaxial strength of specimen with volume V_1
 σ_{c2} = uniaxial strength of specimen with volume V_2
 m = a constant of the material.

After again performing a best fit, the value of m for the Lac du Bonnet grey granite was found to be 16.0 resulting in the scaling curve shown for Weibull in Figure 6. This can be compared with an m value of 12 determined by Lundborg (1966) for granitic specimens. Lundborg, however, used samples whose length was equal to their diameter. Mogi (1966) showed that length/diameter (l/d) ratios of 1 can result in significantly higher compressive strengths than are observed for higher l/d ratios.

TANGENT YOUNG'S MODULUS

When analyzing the stress/strain data, the tangent moduli of elasticity were determined at stress levels of 10, 20, 30, 40, 50, and 60 MPa and at 50% and 75% of the failure stress. This data treatment made it possible to construct a form of pseudo-stress/strain curve (Figure 7) to represent the mean mechanical behaviour for each specimen diameter.

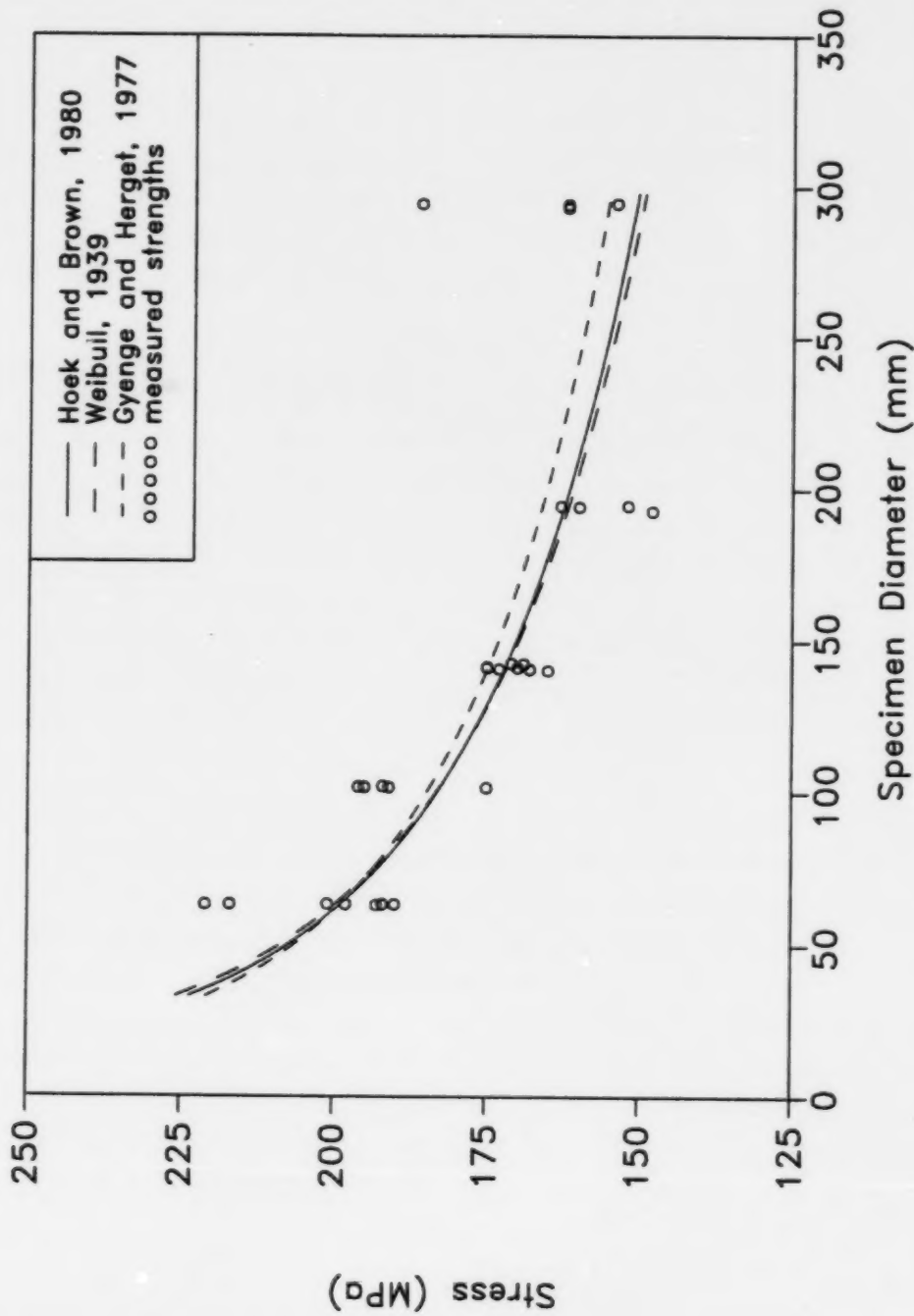


Figure 6: Scaling effect relationships between uniaxial compressive strength and specimen diameter

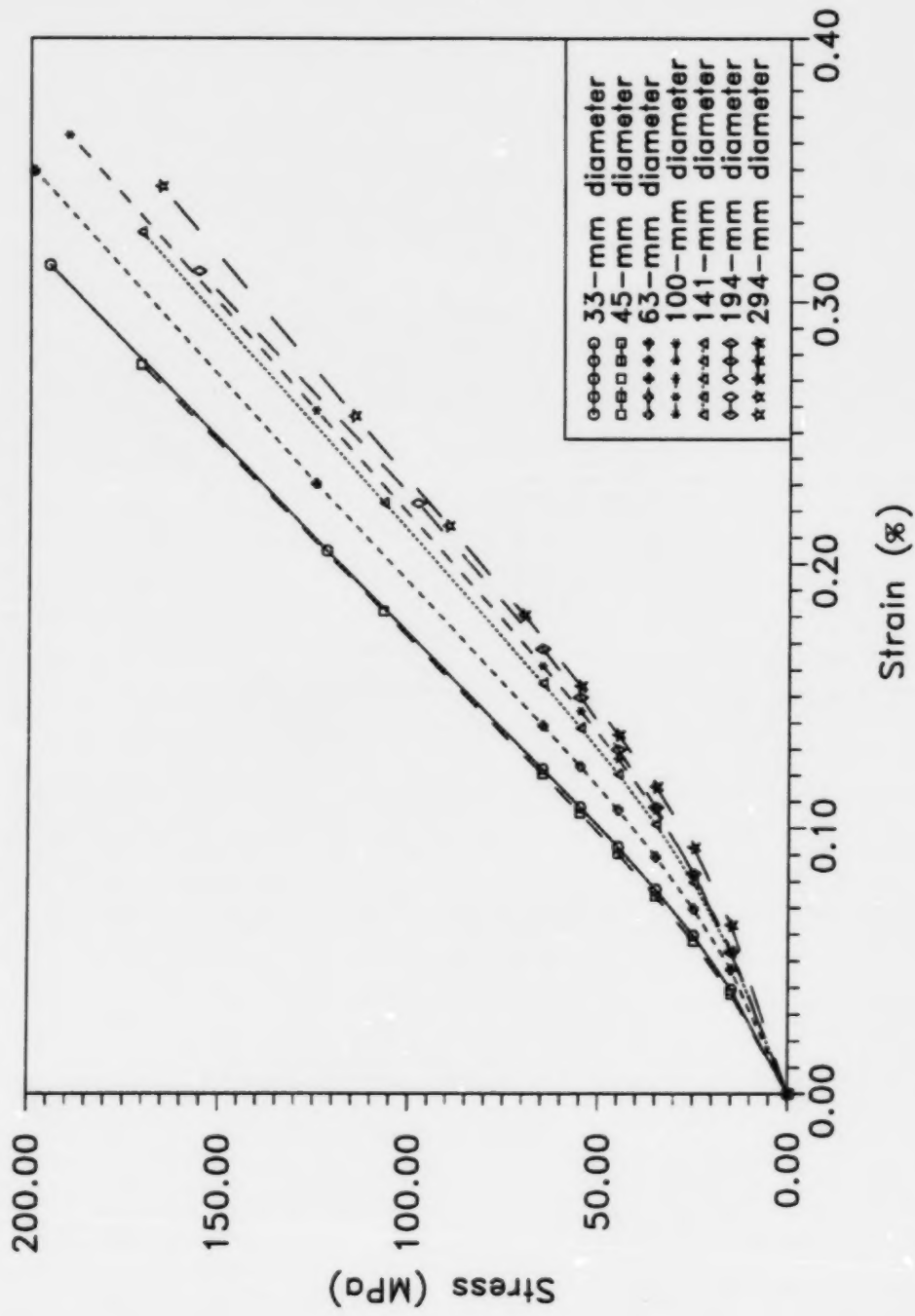


Figure 7: Idealized stress/strain curves for URL scale effects specimens

It appears from the figure that scale does have a significant effect on the tangent modulus at lower stress levels. In fact, at 10 MPa, there is a 27% decrease in tangent modulus as the specimen diameter increases from 63 to 294 mm. With increasing stress, however, the mean moduli tend to converge until there is a maximum difference of only 9% at a stress level of 60 MPa. This implies that there is a higher incidence of open micro-cracks in the larger specimens than existed in the smaller ones. Whether this is a result of greater sample disturbance or strain relief or simply an increased probability of unfavourably oriented micro-cracks in larger specimens as predicted by Weibull is a matter for conjecture. As the zone of linear-elastic behaviour is approached, however, differences in moduli diminish as one might expect in a relatively homogeneous rock like the Lac du Bonnet grey granite. Similarly, higher confining pressures should tend to reduce any scale effect on the observed moduli.

POISSON'S RATIO

Poisson's ratio, ν , was determined for each sample at 50% of its failure load. At this stress level, the influence of crack closure or propagation on the deformational properties of hard rock is minimal (Lama and Vutukuri, 1978). As might be expected then, there appears to be little correlation between ν and specimen diameter (Figure 9). The inordinately high value of 0.42 for the mean Poisson's ratio determined for the 33 mm diameter specimens is likely more a result of machine/specimen interaction than an intrinsic property of the rock.

CONCLUSIONS

In general, it appears that a number of influences determine the observed mechanical behaviour of specimens up to 63 mm in diameter which are difficult to quantify in the analyses. Definite trends of decreasing uniaxial compressive strength and tangent modulus of elasticity, however, are evident as the specimen diameter increases from 63 mm to 294 mm. This decrease is well explained by the increased probability of the existence of a critical flaw or flaws in larger specimens (Weibull's "weakest link" theory) and is adequately described by any of the Hoek and Brown, Gyenge and Herget or Weibull models. In terms of Canada's Nuclear Fuel Waste Management Program, it becomes important to determine if this effect will be enhanced by the thermal loading anticipated in a waste vault environment.

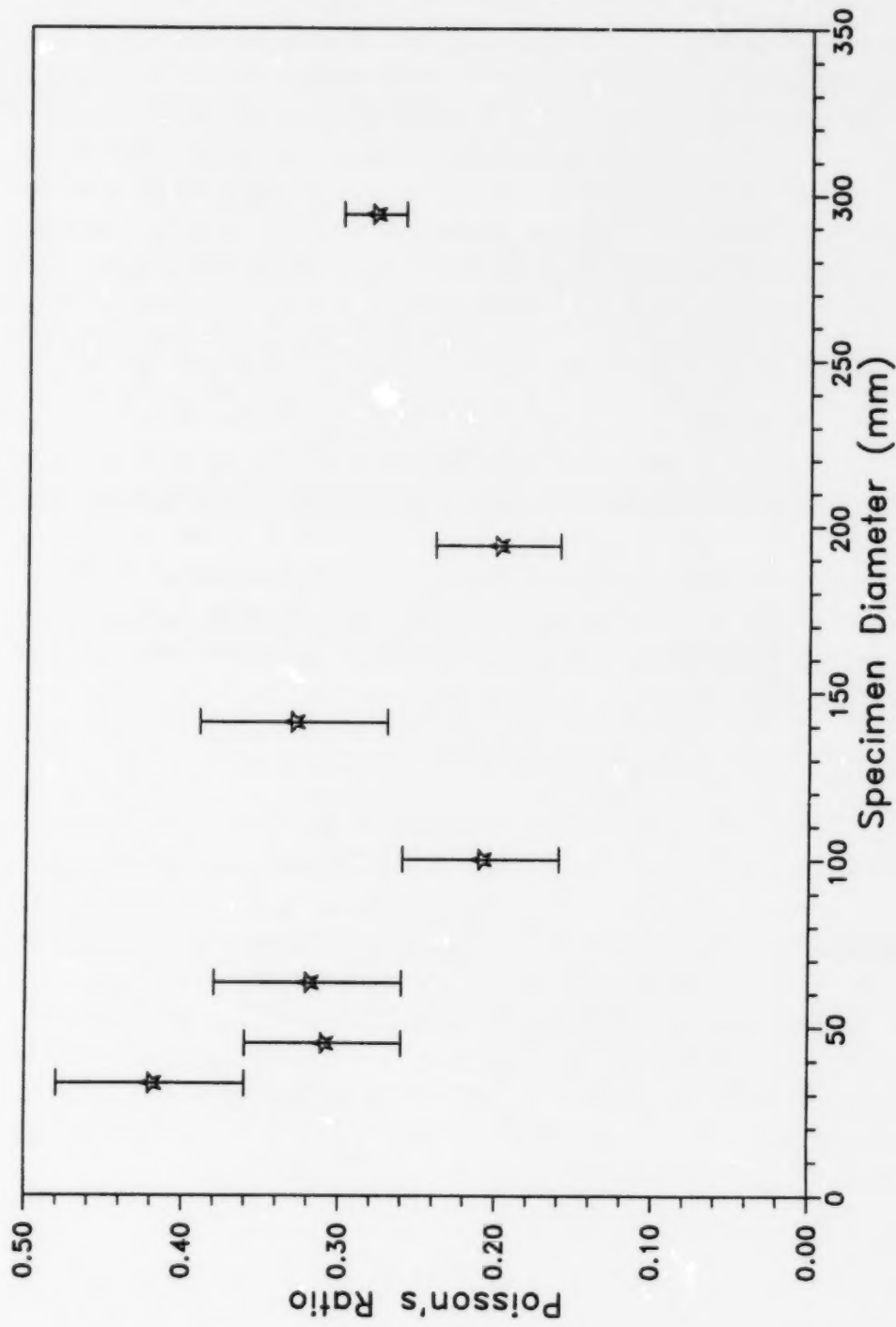


Figure 8: Poisson's Ratio versus specimen diameter

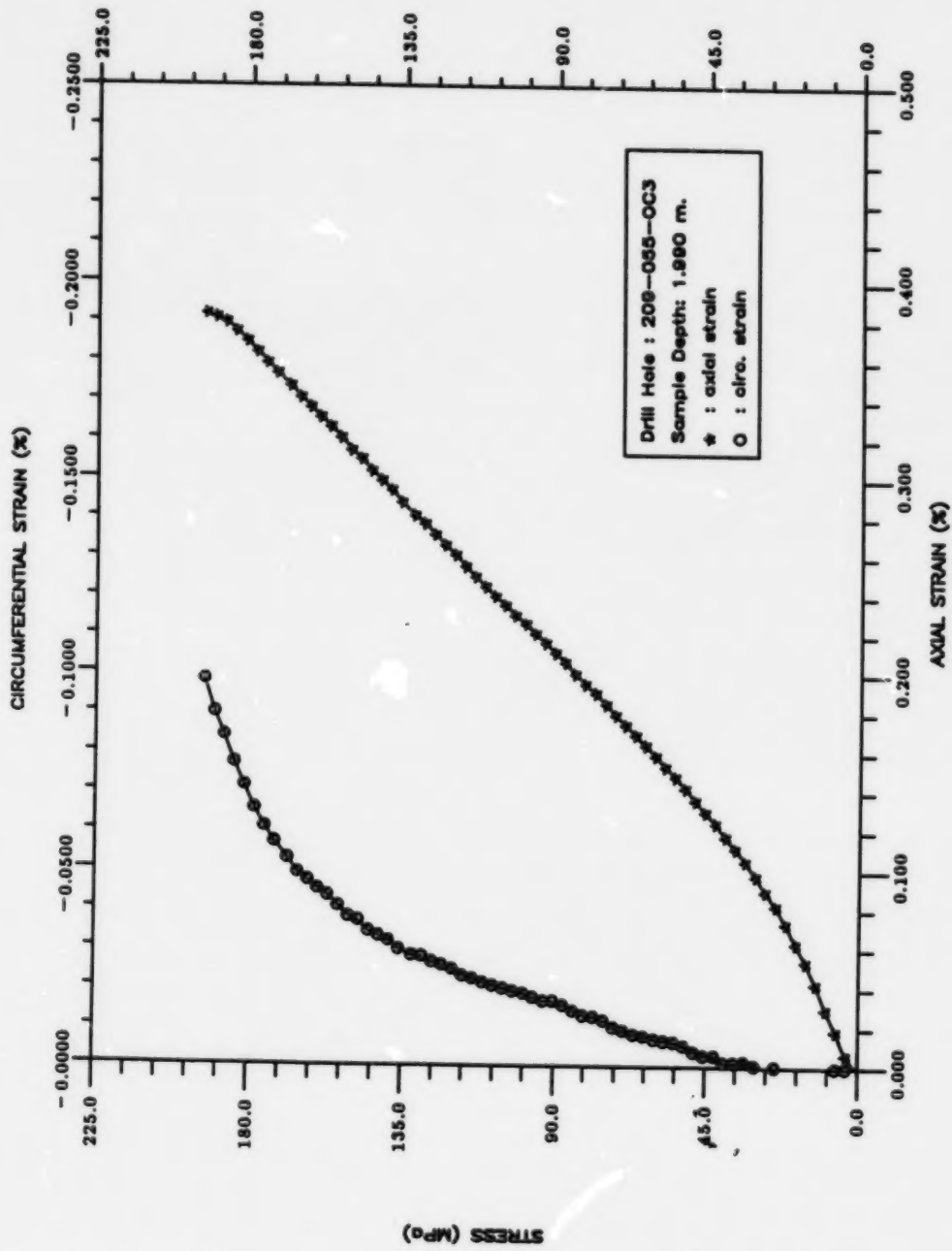


Figure 9: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

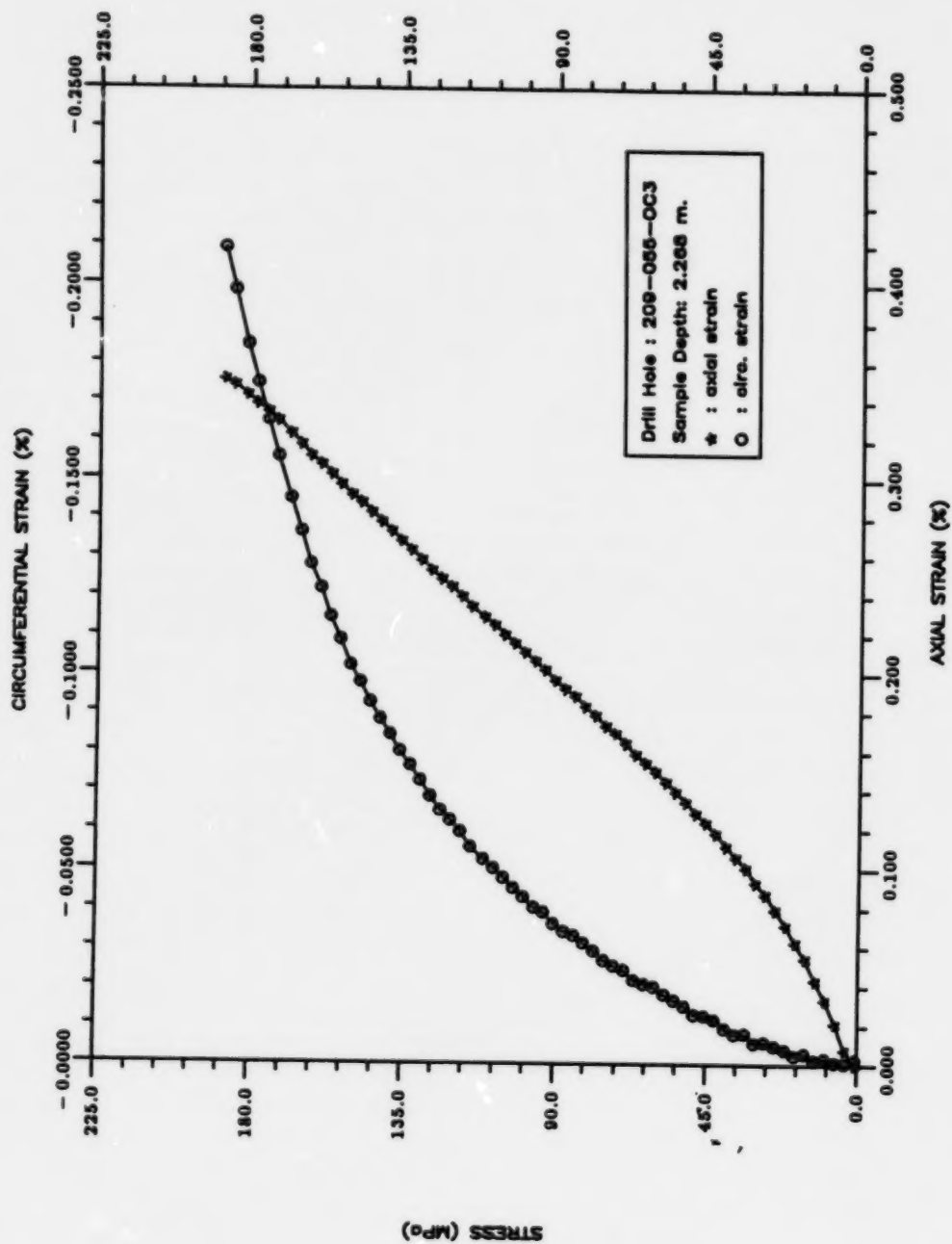


Figure 10: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

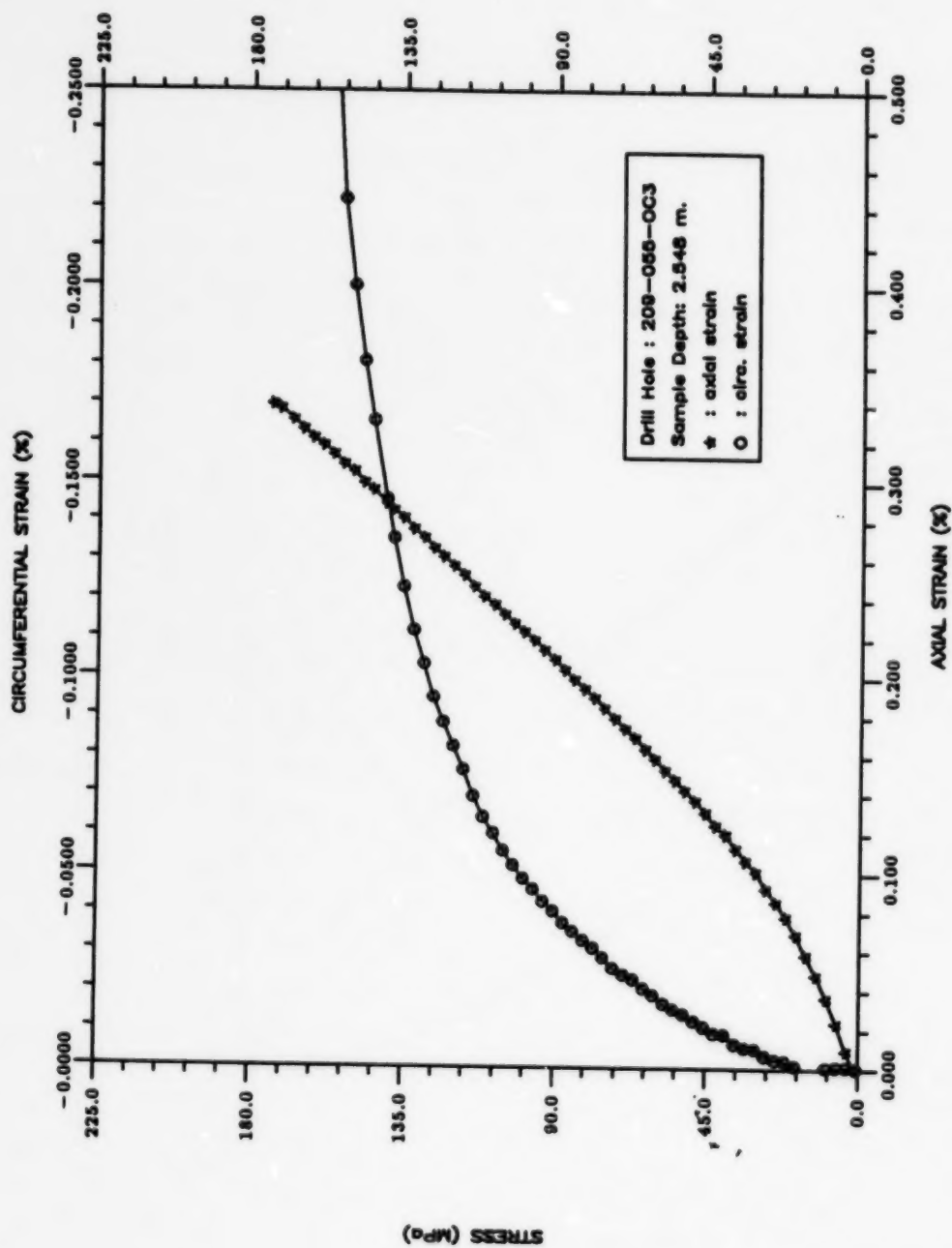


Figure 11: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

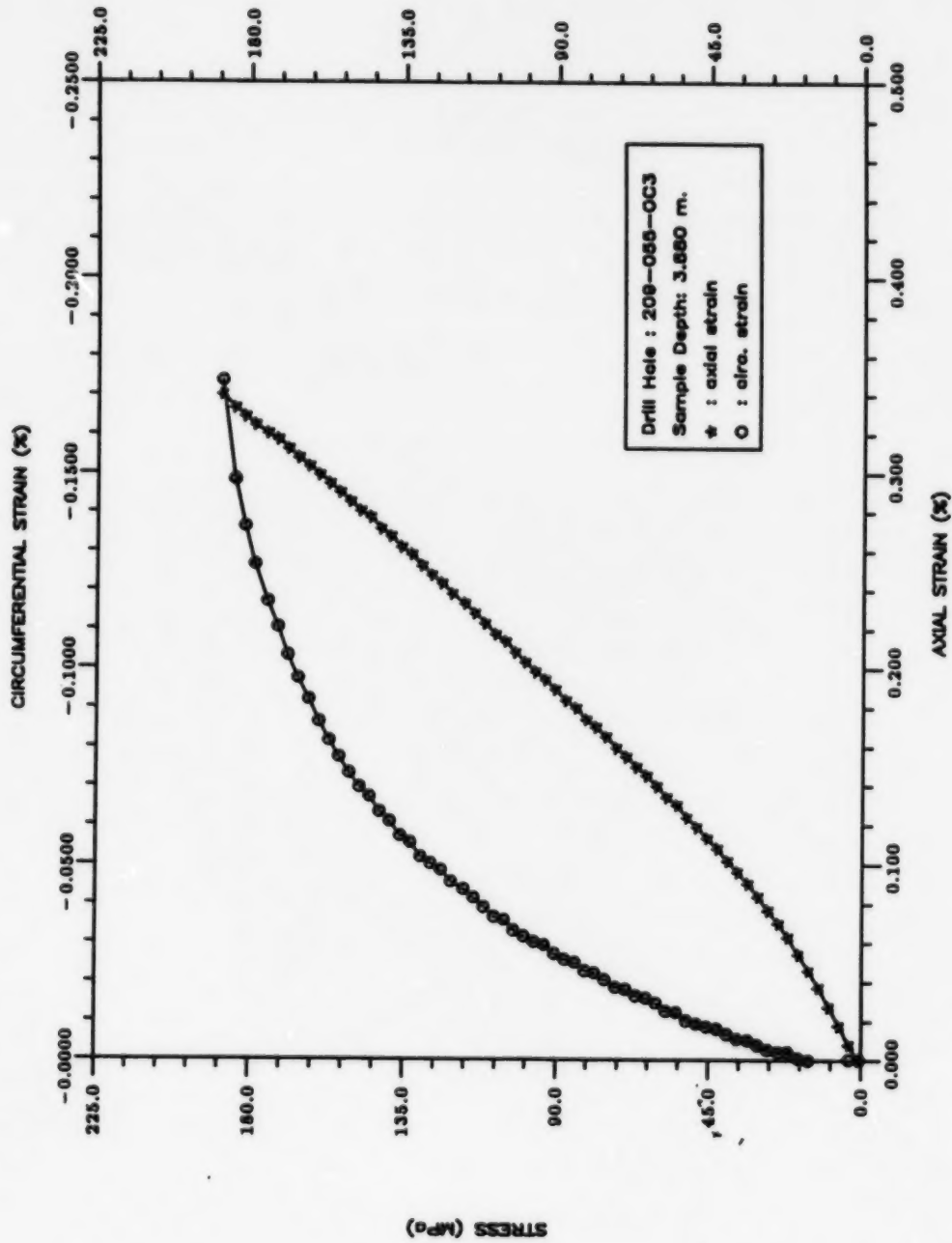


Figure 12: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

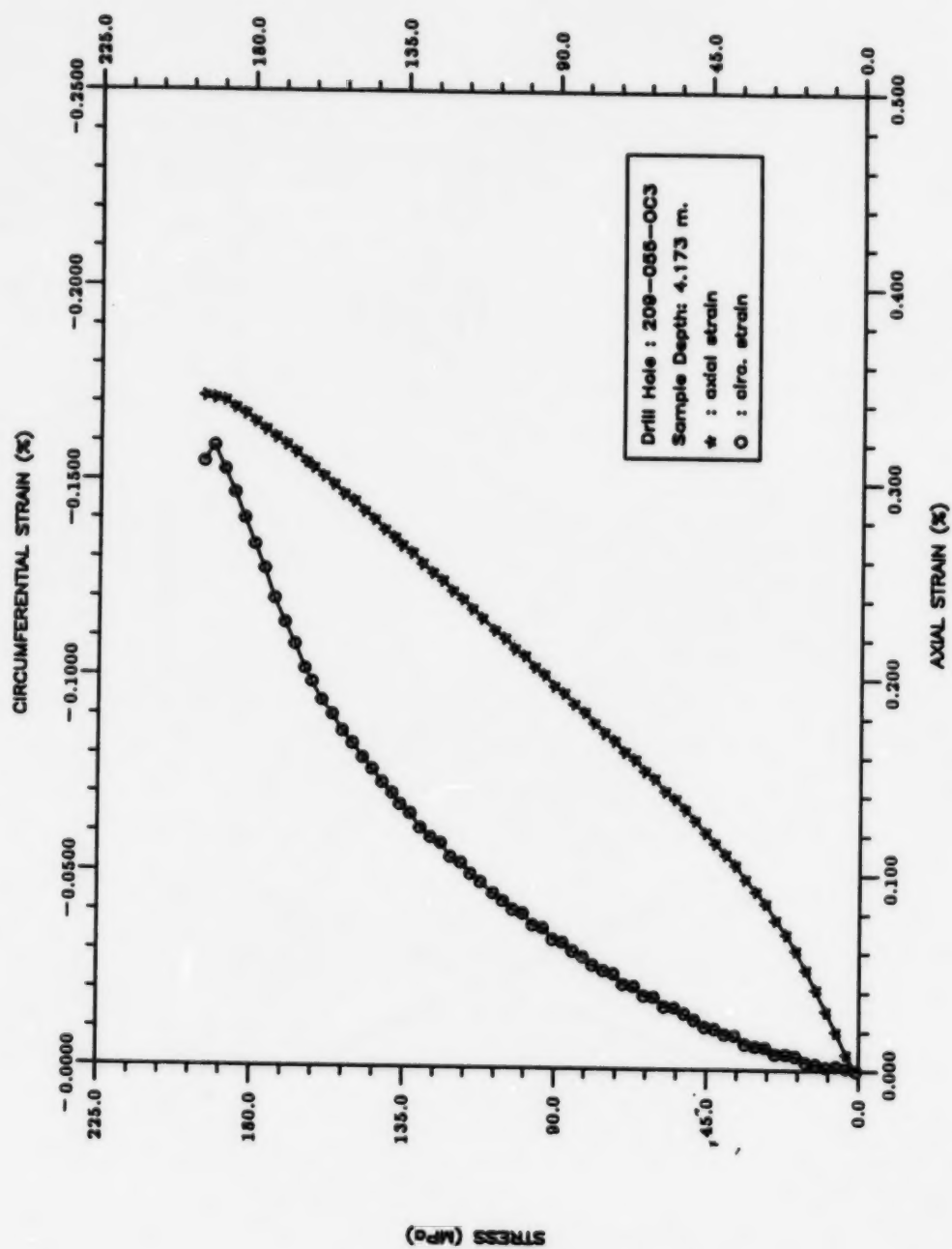


Figure 13: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

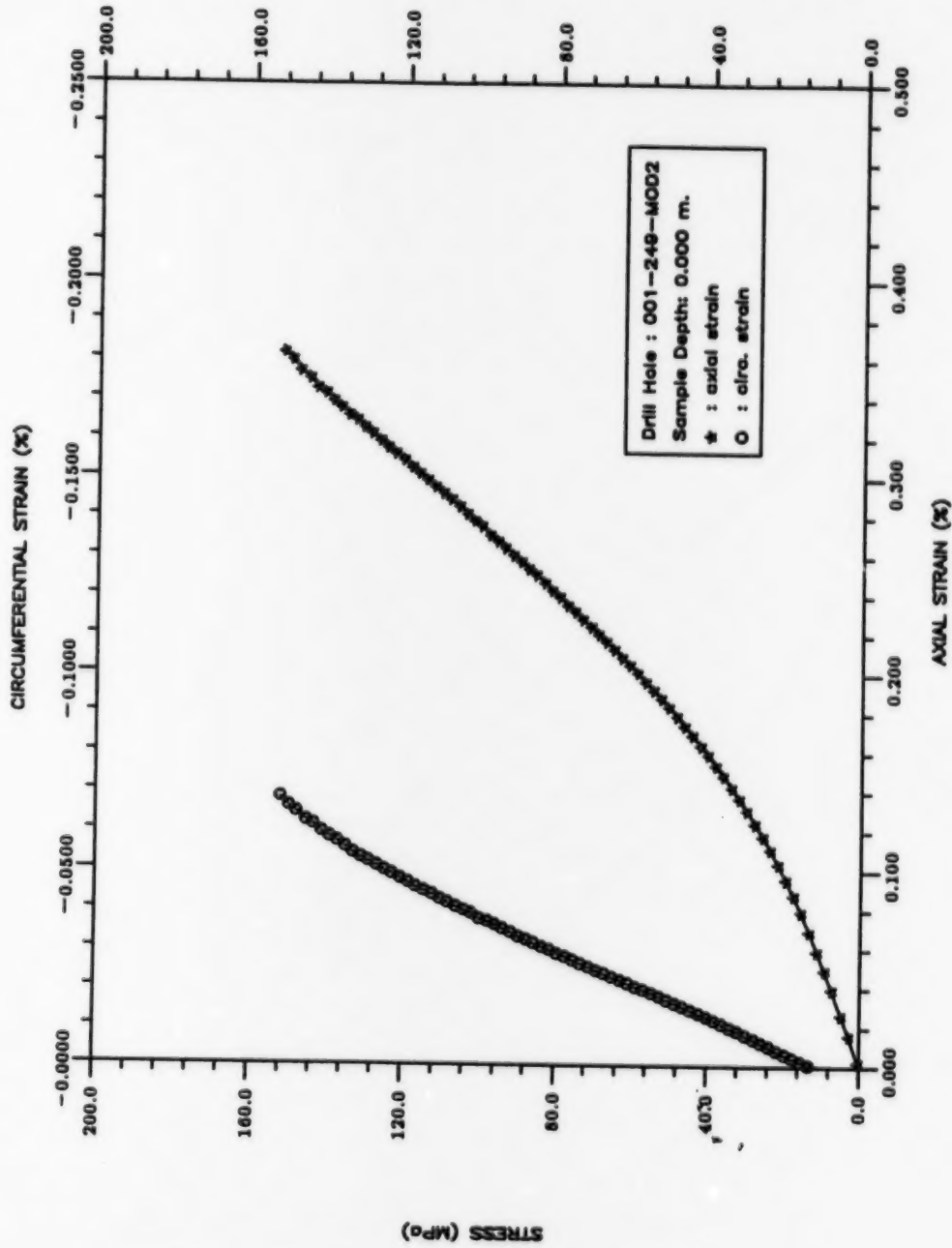


Figure 14: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

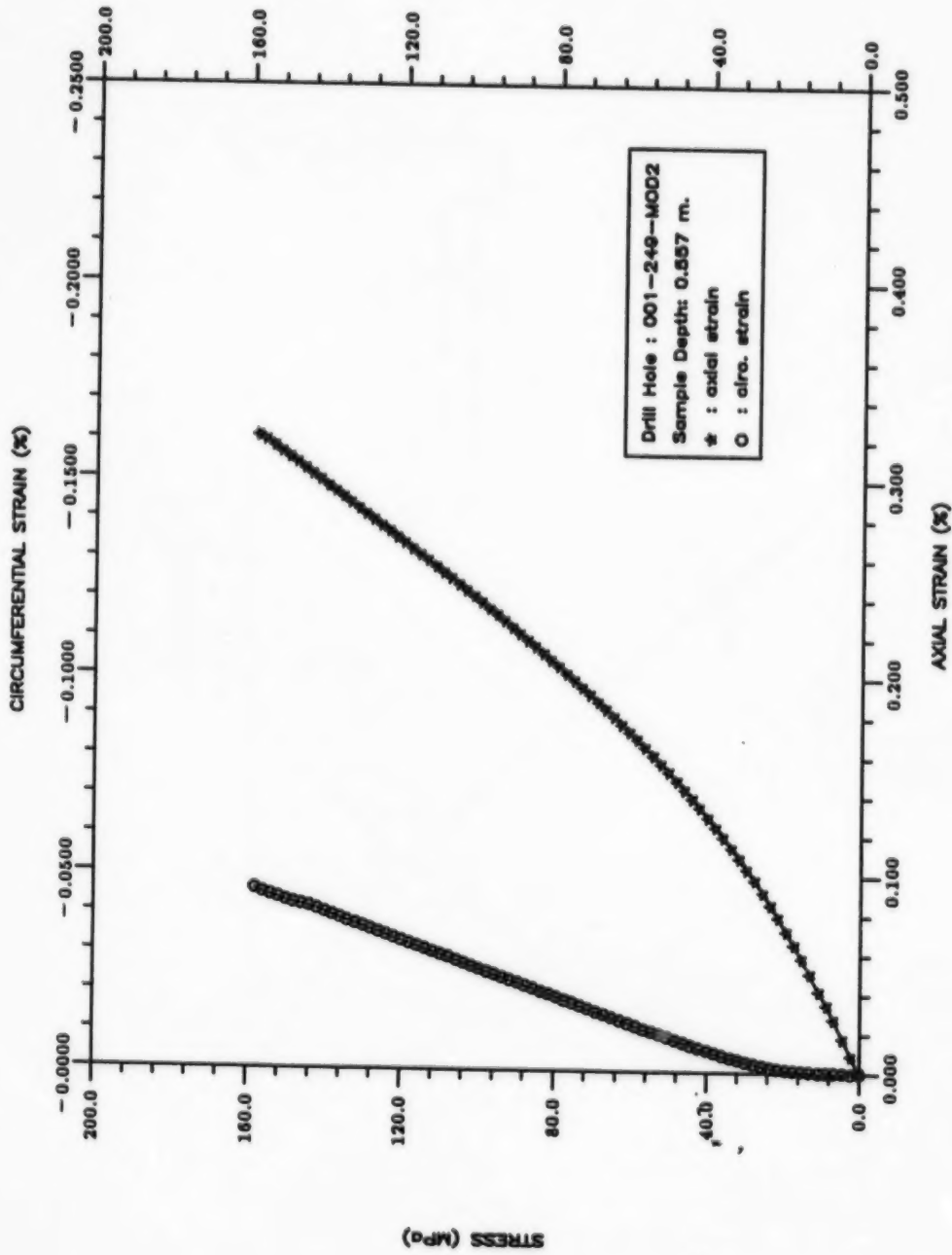


Figure 15: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

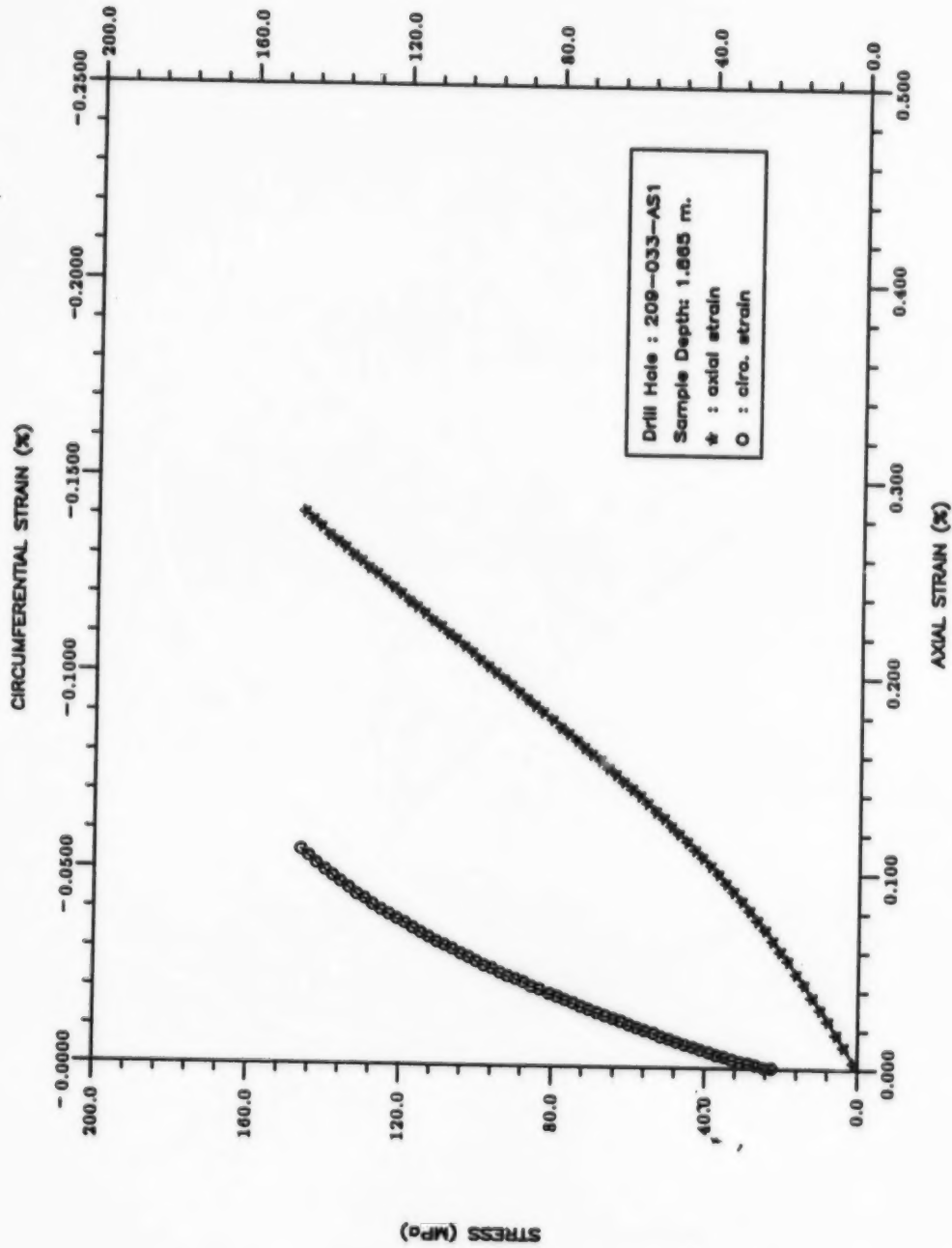


Figure 16: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

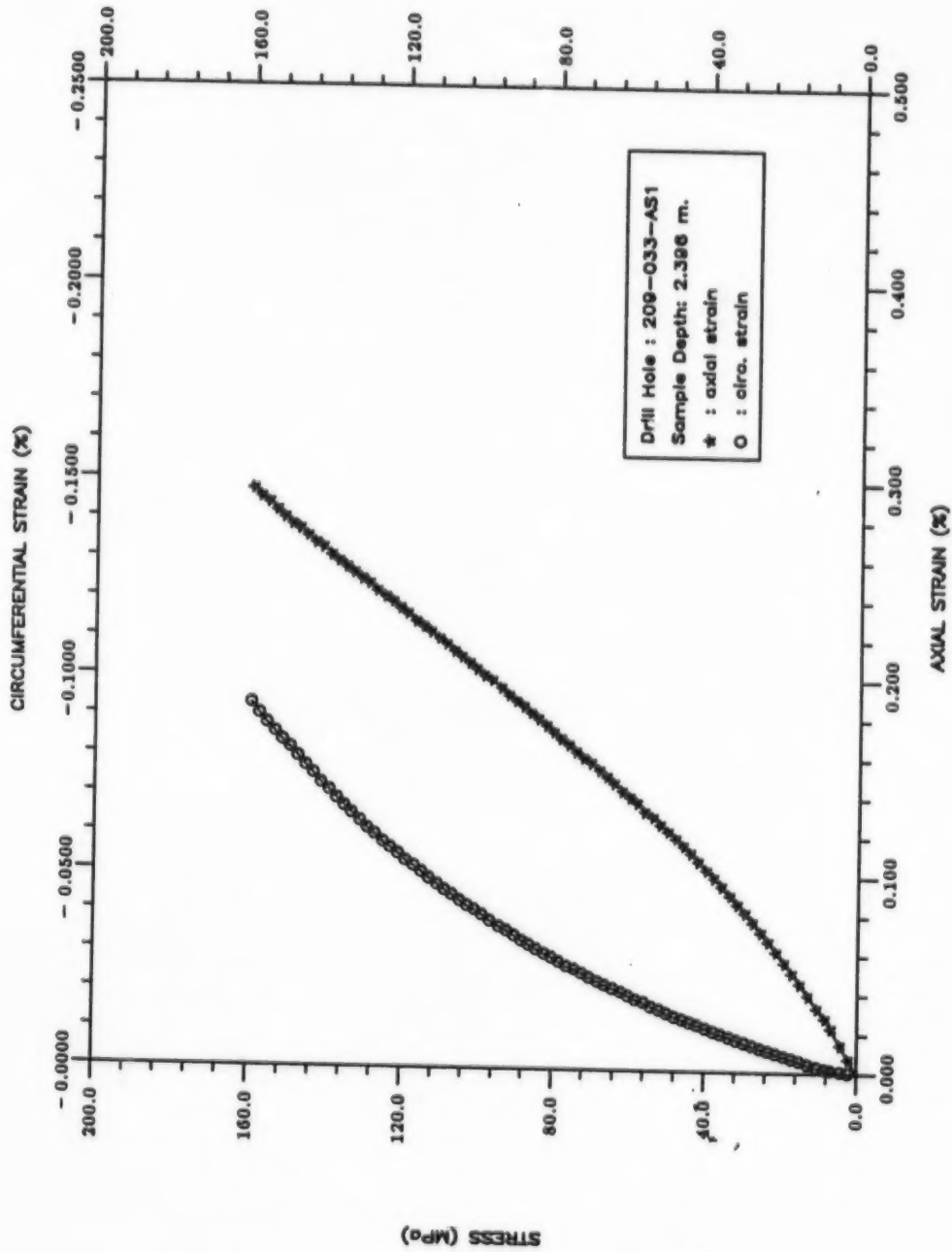


Figure 17: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

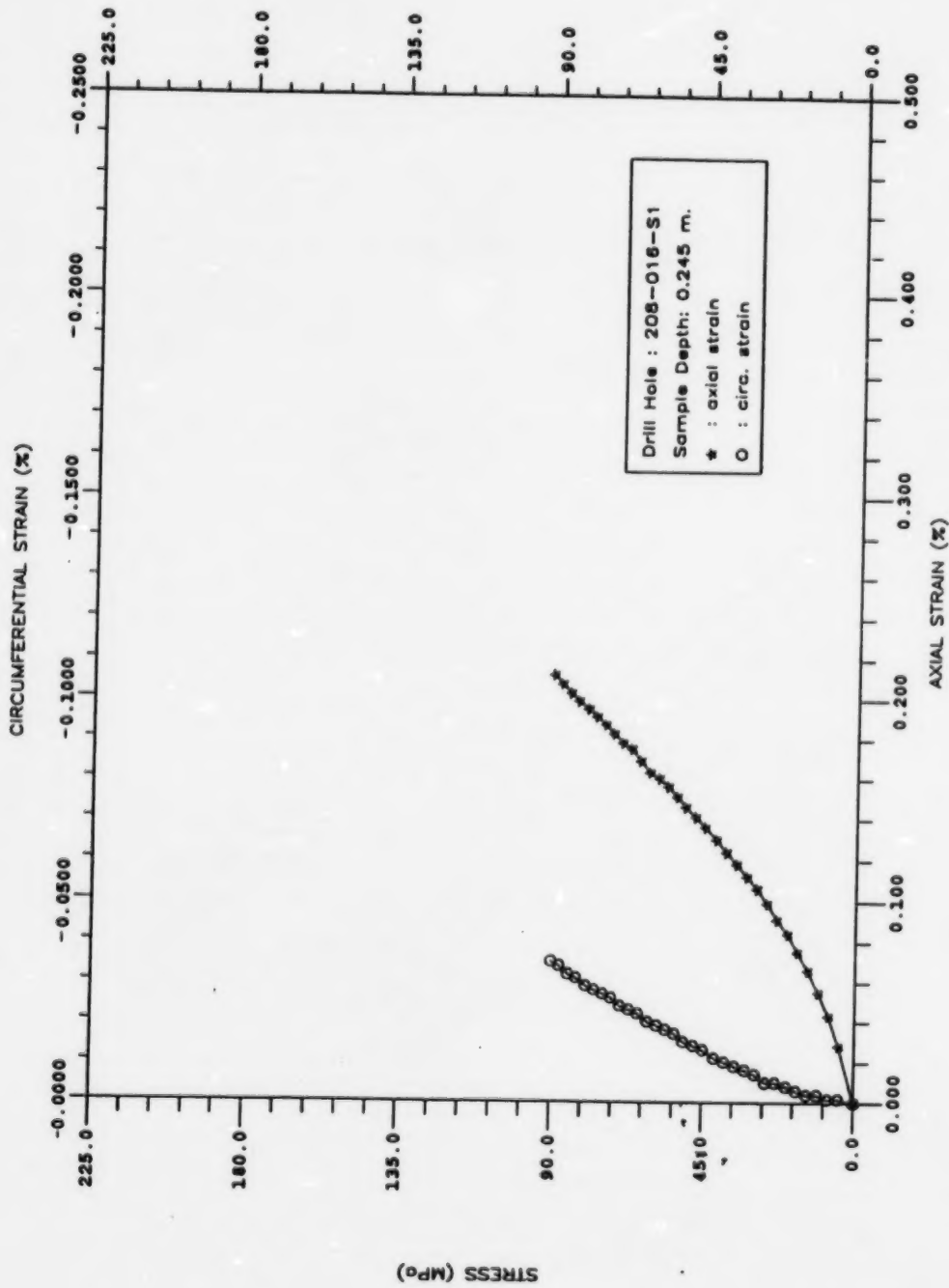


Figure 18: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

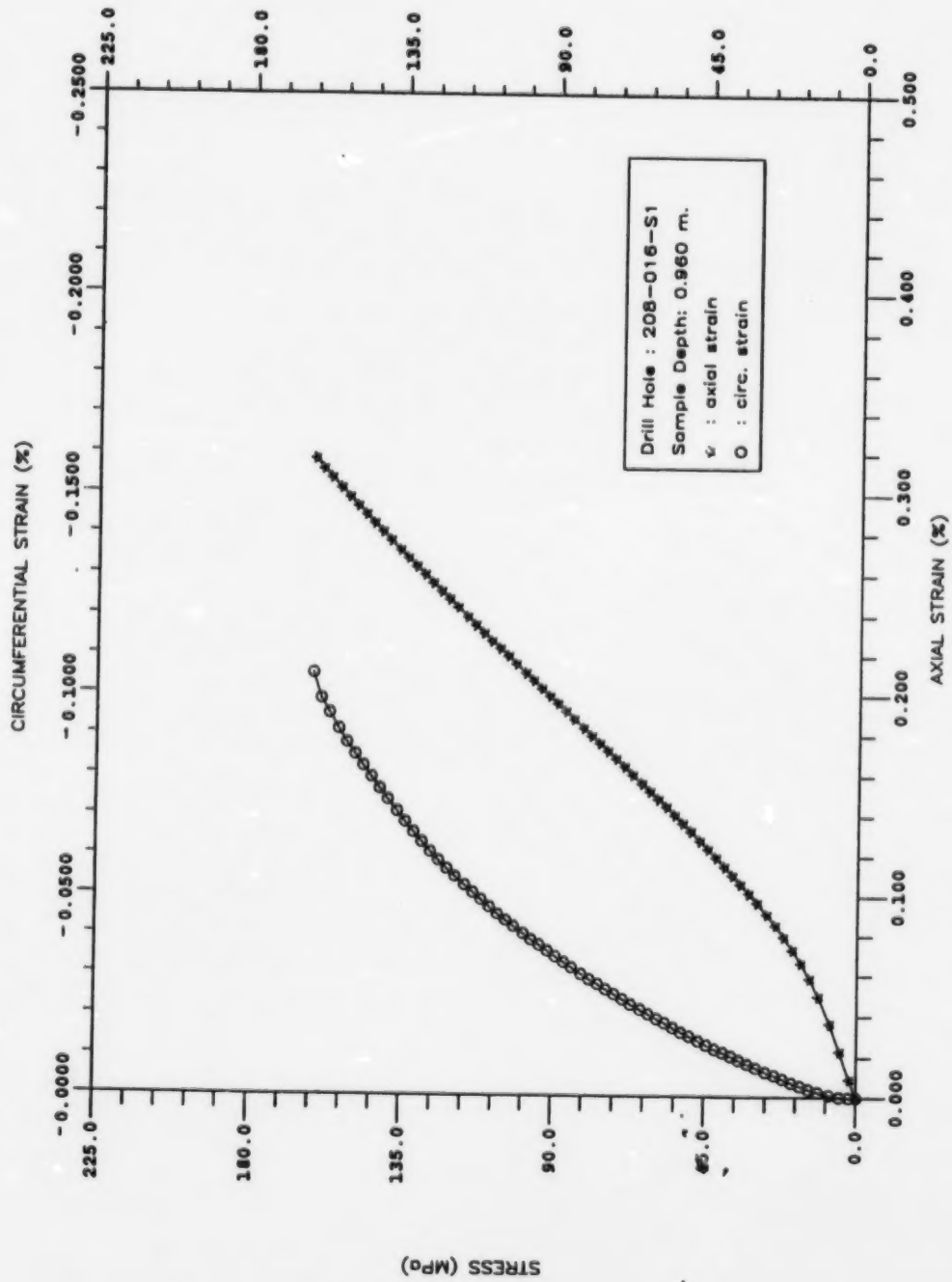


Figure 19: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

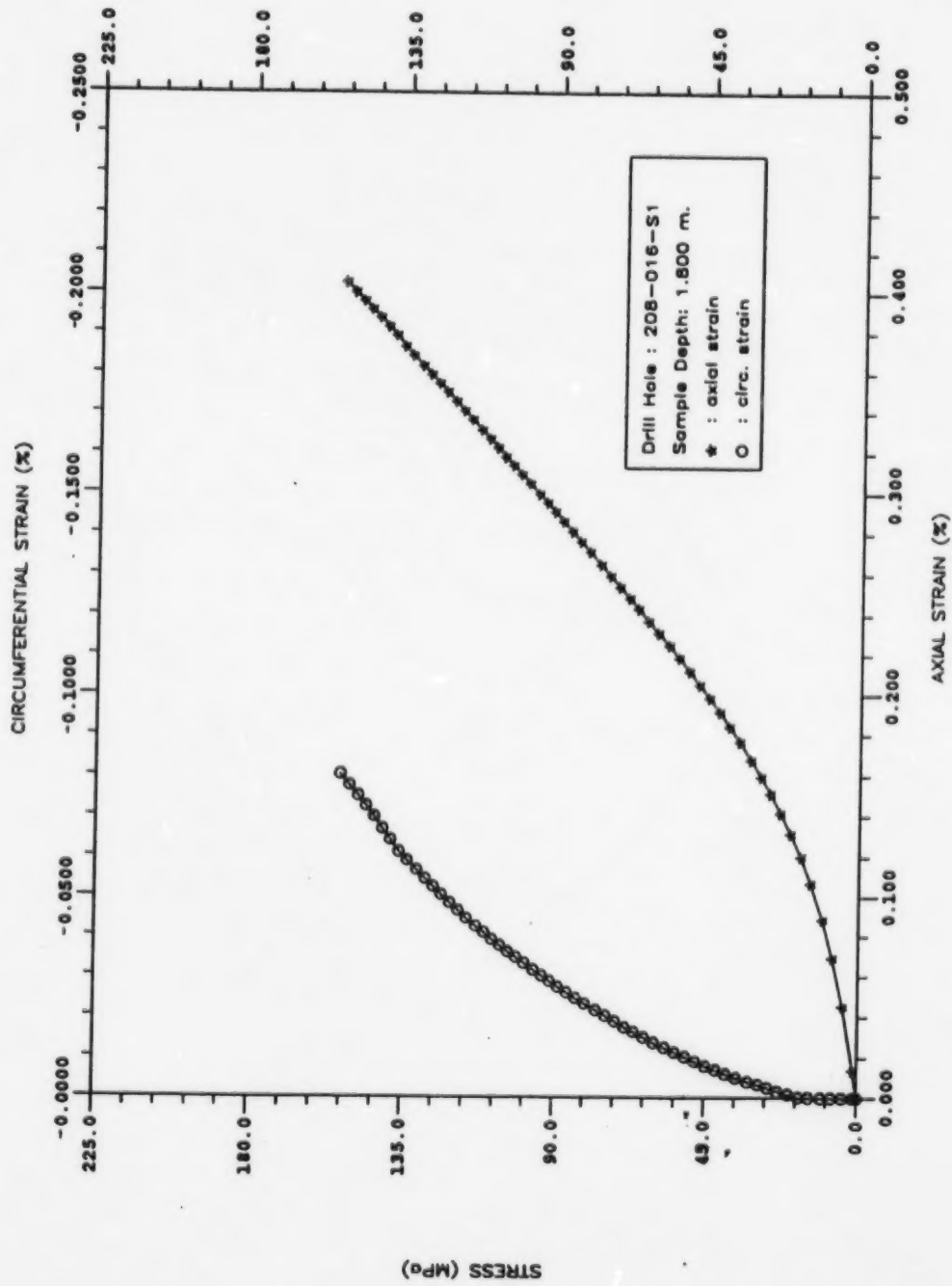


Figure 20: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

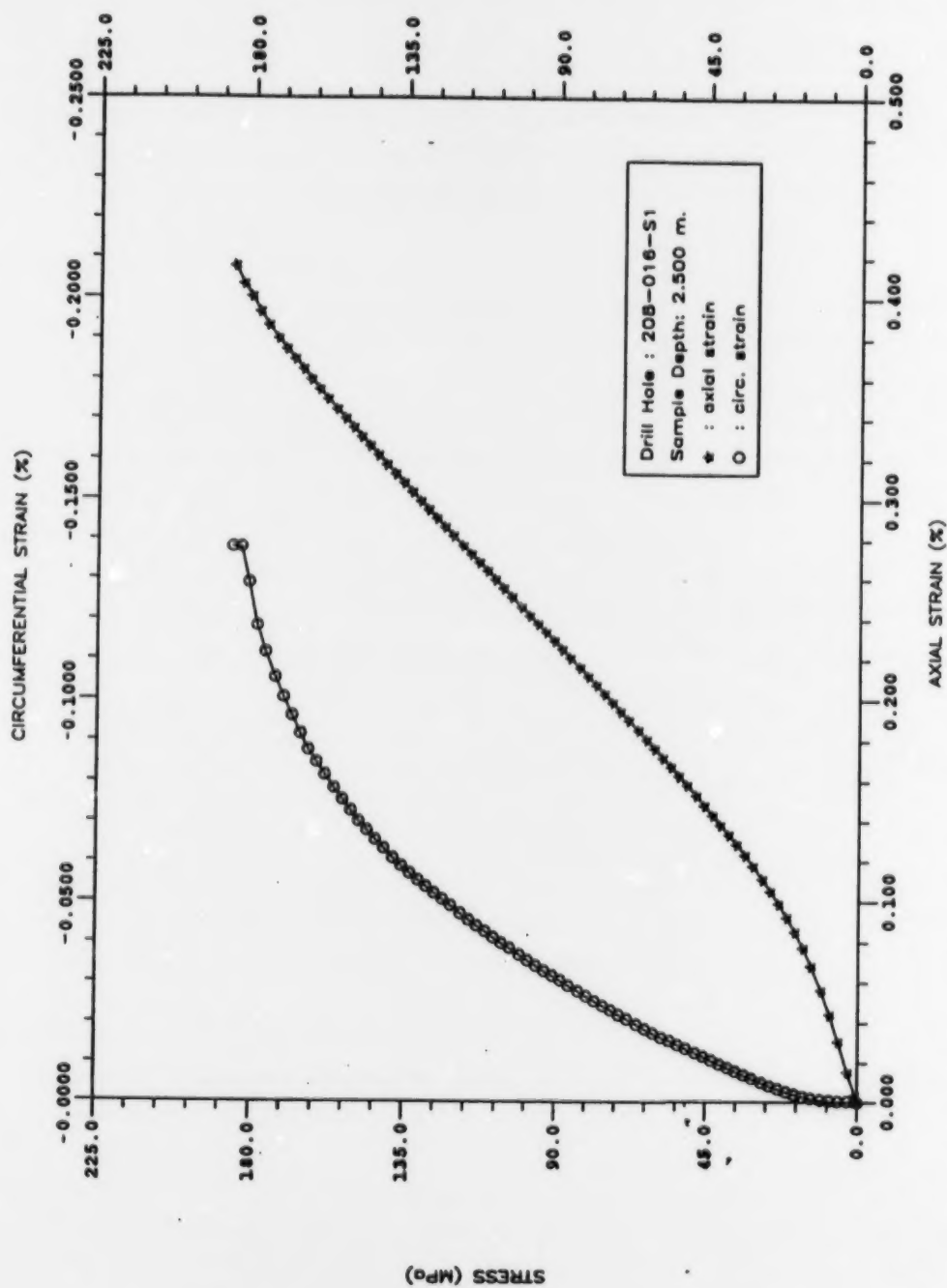


Figure 2l: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimens

REFERENCES

1. E.T. Brown
Rock characterization testing and monitoring, ISRM suggested methods, International Society for Rock Mechanics, the Commission on Testing Methods, Pergamon, 1981.
2. R.K. Dhir and C.M. Sangha
Relationships between size, deformation and strength for cylindrical specimens loaded in uniaxial compression, *Int. J. Rock Mech. Min. Sci.* 4; 269-272, 1973.
3. M. Gyenge and G. Herget
Pit slope manual chapter 3 - mechanical properties, CANMET Report 77-12, 1977.
4. M. Gyenge and B. Ladanyi
Pit slope manual supplement 3-5 - sampling and specimen preparation, CANMET Report 77-29, 1977.
5. K. Hodgson and N.G.W. Cook
The effect of size and stress gradient on the strength of rock, *Proc. 2nd Cong. Int. Soc. of Rock Mech.*, Belgrade, 1970.
6. E. Hoek and E.T. Brown
Underground Excavation in Rock, The Institution of Mining and Metallurgy, London, 1980.
7. J.R. Hoskins and F.G. Horino
Influence of spherical head size and specimen diameters on the uniaxial compressive strength of rocks, BuMines Rept. of Inv. 7234, 1969.
8. J.A. Hudson, E.T. Brown and C. Fairhurst
Shape of the complete stress-strain curve for rock, *Proc. 13th Symp. Rock Mech.*, Urbana, Ill, 1971.
9. R. Jackson
Anisotropic properties study of Lac du Bonnet granite specimens: Report No. 5, Division Report MRL 88-39(TR), CANMET, Energy, Mines and Resources Canada, 1988.

10. R.D. Lama
In situ and laboratory strength of coal, Proc. 12 Symp. Rock Mech., Rolla, Missouri, 1970.
11. R.D. Lama and V.S. Vutukuri
Handbook on mechanical properties of rocks, Switzerland:Trans Tech Aedermansdorf, 1978.
12. N. Lundborg
The strength-size relation of granite Int. J. Rock Mech. Min. Sci., 4: 269-272, 1966.
13. K. Mogi
Some precise measurements of fracture strength of rocks under uniform compressive stress, Rock Mech. Eng. Geol., Vol. 4, 1966: 175-185, 1966.
14. V.S. Vutukuri, R.D. Lama, and S.S. Saluja
Handbook on mechanical properties of rocks, Bay Village:Trans Tech Publications, 1974.
15. W.A. Weibull
A statistical theory of the strength of materials, Proc. R. Swedish Acad. Engng Sci., 1939.